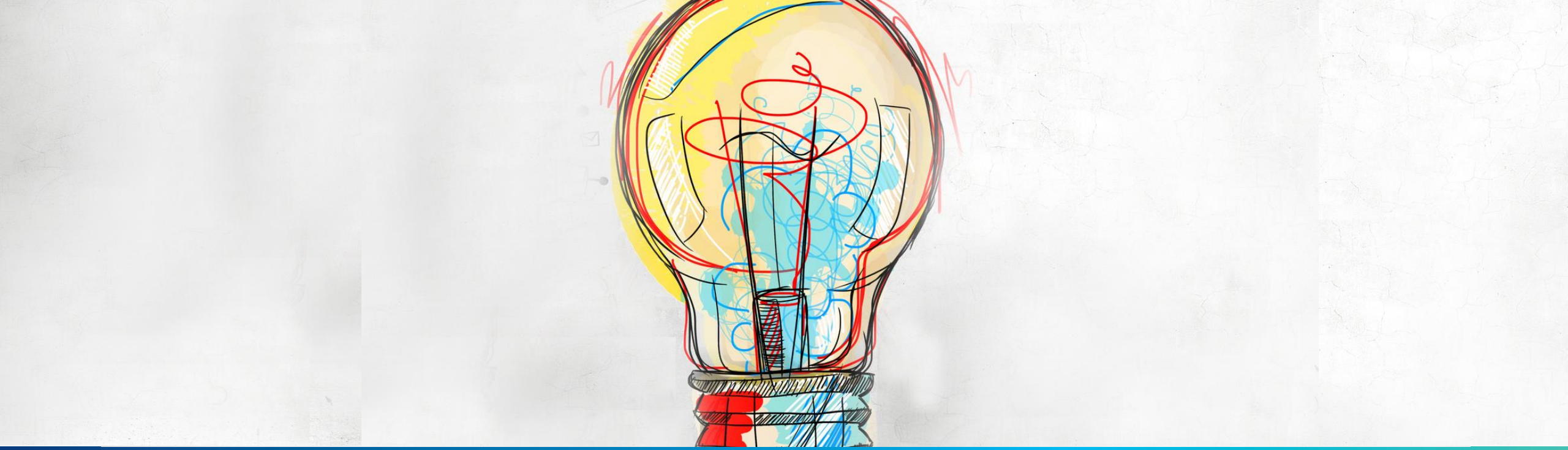


Intro to Small Modular Reactors:

The technology, the economics, and the politics. IEEE Alberta Webinar. Jan 20, 2021

Denys Elliot
Commercial Lead – SMR Program

Megan Moore
Operations Research Analyst

Metin Yetisir
Senior Research Scientist

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

DELIVERING THE **SCIENCE OF TOMORROW,** TODAY.

NAYGN
NORTH AMERICAN YOUNG GENERATION IN NUCLEAR

Webinar Agenda

1. Intro to CNL
2. What are SMRs?
3. Nuclear Power and SMRs
    a) Nuclear Power Explained
    b) Traditional Nuclear Reactors
    c) SMRs
4. Economics of SMRs
5. Latest developments
6. Q&A

Canadian Nuclear Laboratories

A national lab focused on national priorities.

- Canada's national nuclear laboratory
- Over 50 unique laboratories, 9000 acre campus
- Diverse team of >500 researchers
- Broad portfolio in science

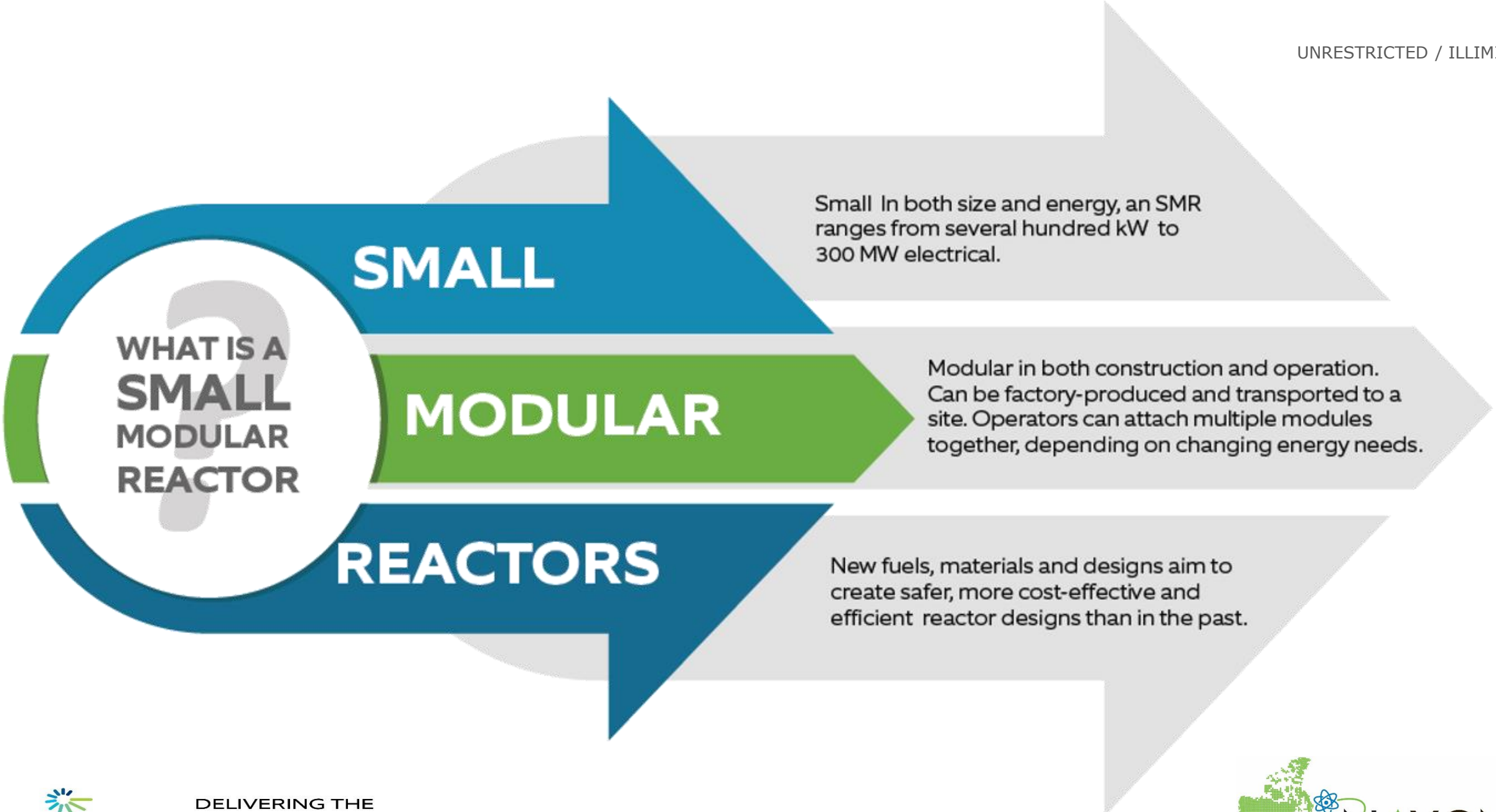
Canadian Nuclear Laboratories (CNL) is a private sector company with a contract to manage and operate the nuclear research facilities on behalf of Atomic Energy of Canada Limited (AECL), a federal crown corporation

Chalk River Laboratories (CRL), the key asset under CNL management, is located in the Upper Ottawa Valley and a significant employer in the region

Restore and protect the environment

Clean energy for today and tomorrow

Improve the health of Canadians


WHAT IS A SMALL MODULAR REACTOR
SMALL
Small In both size and energy, an SMR ranges from several hundred kW to 300 MW electrical.
MODULAR
Modular in both construction and operation. Can be factory-produced and transported to a site. Operators can attach multiple modules together, depending on changing energy needs.
REACTORS
New fuels, materials and designs aim to create safer, more cost-effective and efficient reactor designs than in the past.

Nuclear Power and Small Modular Reactors (SMR):

A Clean Energy Option for Canada

2021 January

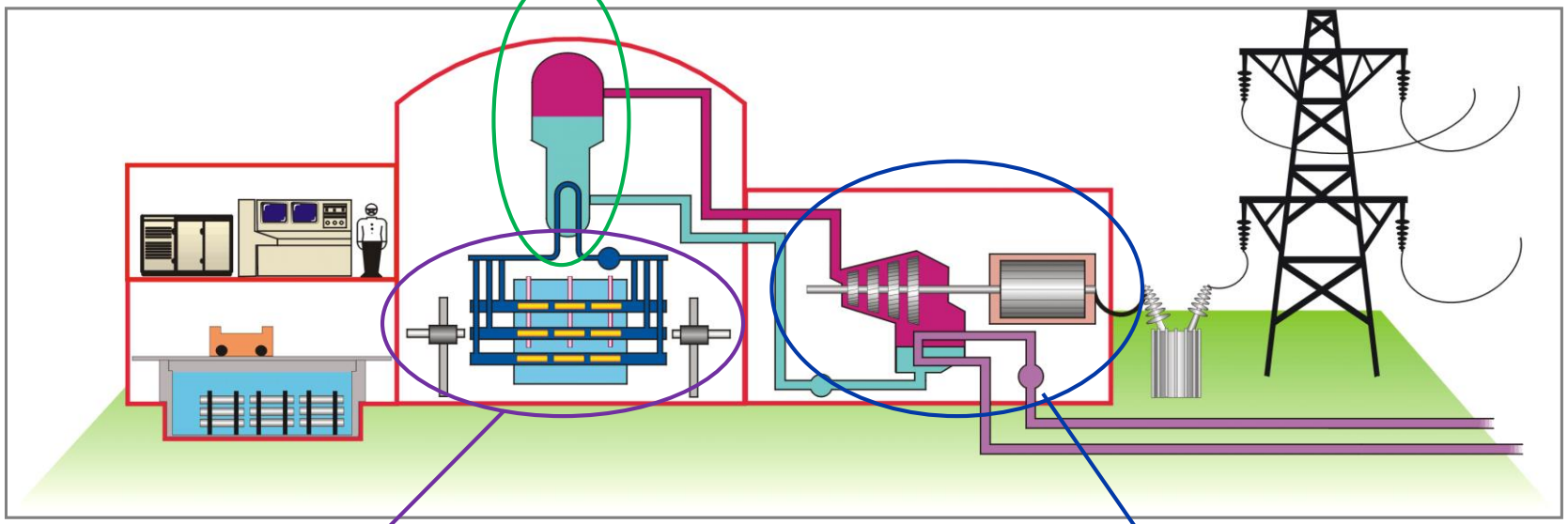
Metin Yetisir

Contents

- Nuclear 101 - How does a nuclear plant work?
- Nuclear Reactor Design
- Current Fleet of Nuclear Reactors
- Advanced Reactors and Small Modular Reactors

A typical nuclear power plant and electricity generation

Transfer and Transport Energy to Secondary Side (produce steam)



Produce Power

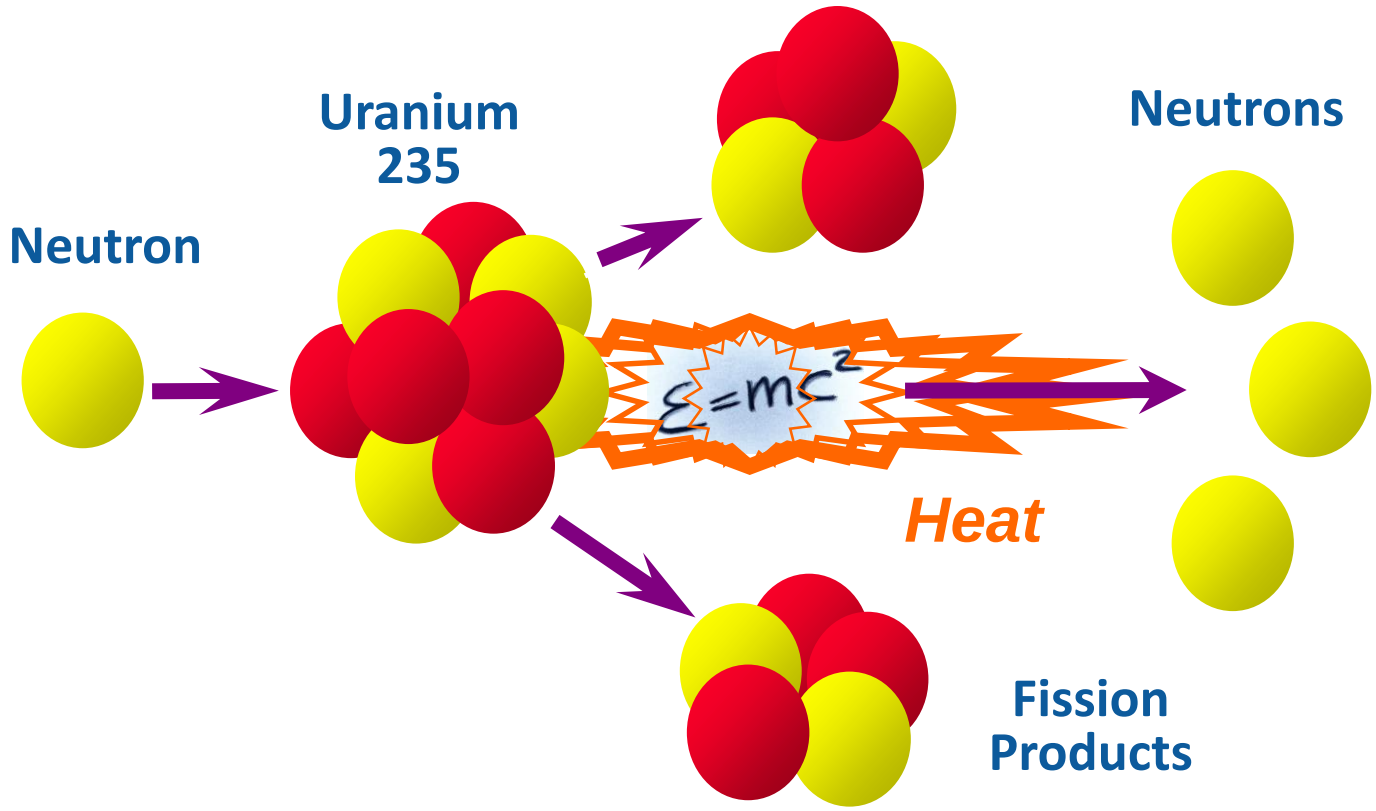
Convert to Electricity

About 10% of the world's electricity is produced by 450 nuclear reactors

(2019 Data from https://www.iaea.org/newscenter/news/preliminary-nuclear-power-facts-and-figures-for-2019)

Nuclear Fission

A clean source of energy.



Neutrons do all the work!!!

Nuclear reactor technology is based on generating neutrons (via splitting atoms) and controlling neutron population.

Recipe for a Nuclear Reactor

List of Ingredients:

- Fuel: Uranium, Plutonium, Thorium
- Moderator: Water, graphite
- Coolant: Water, Helium, molten-salt, liquid metal (sodium, lead)
- Control Rods: Neutron absorbing materials like Boron or Cadmium

Types of Reactors (1/2)

Nuclear reactors can be classified in different ways. The most common classifications are according to

Coolant Type:

- Water-cooled reactors – light water, heavy water, supercritical water
- Gas-cooled reactors – helium, CO2
- Molten-salt reactors – various fluoride or chloride salts
- Liquid metal reactors - sodium, lead

Neutron Speed:

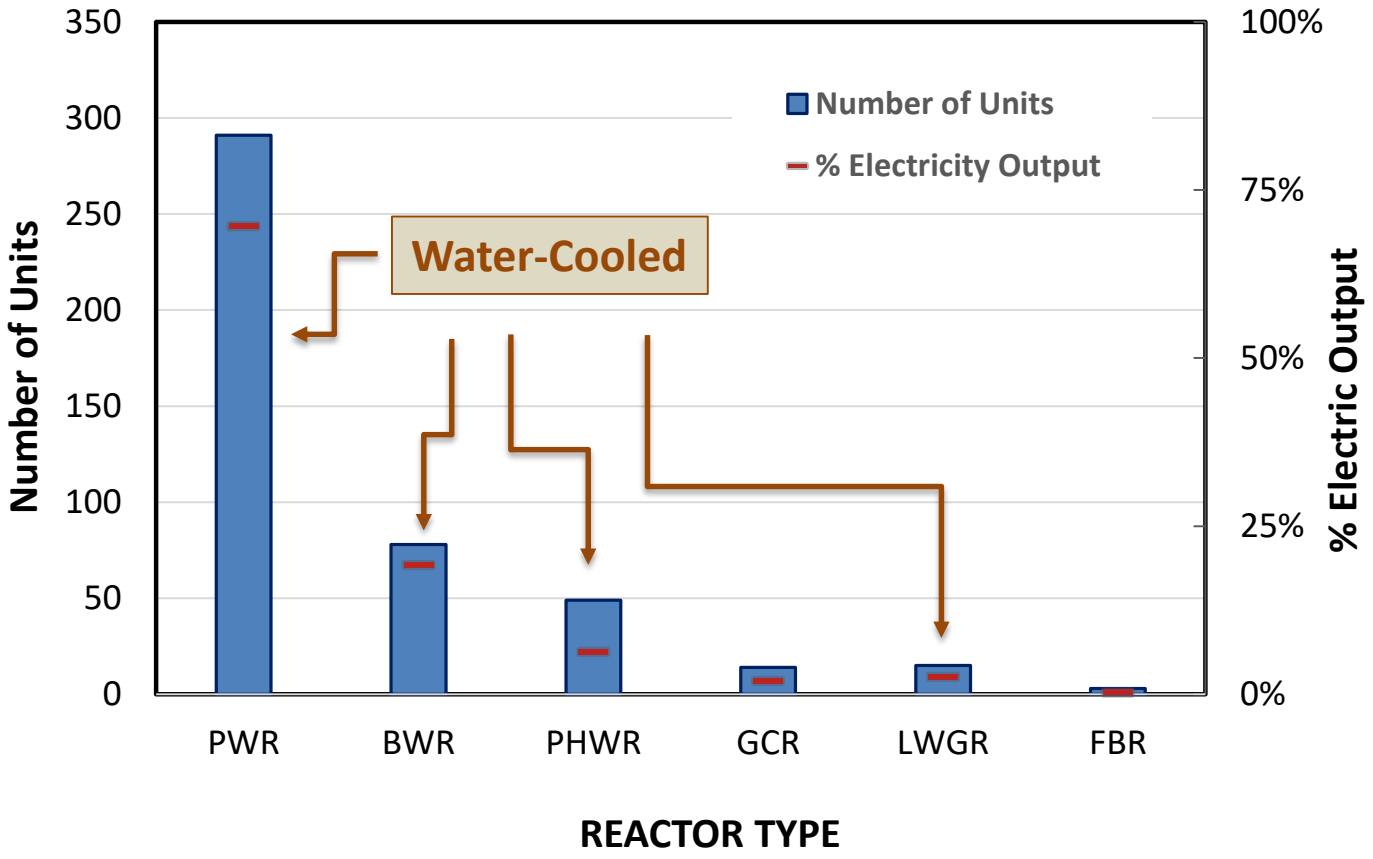
- Fast reactor – no moderator, enriched fuel to maintain fission reaction
- Thermal reactor – uses moderators to slow down neutrons

Types of Reactors (2/2)

- Water-cooled reactors: PWRs, BWR, and PHWR

- Non-water-cooled advanced reactors
  - High Temperature Gas Cooled Reactor
  - Sodium Cooled Reactor
  - Lead-Cooled Reactor
  - Molten Salt Reactor

Existing Fleet of Nuclear Reactors

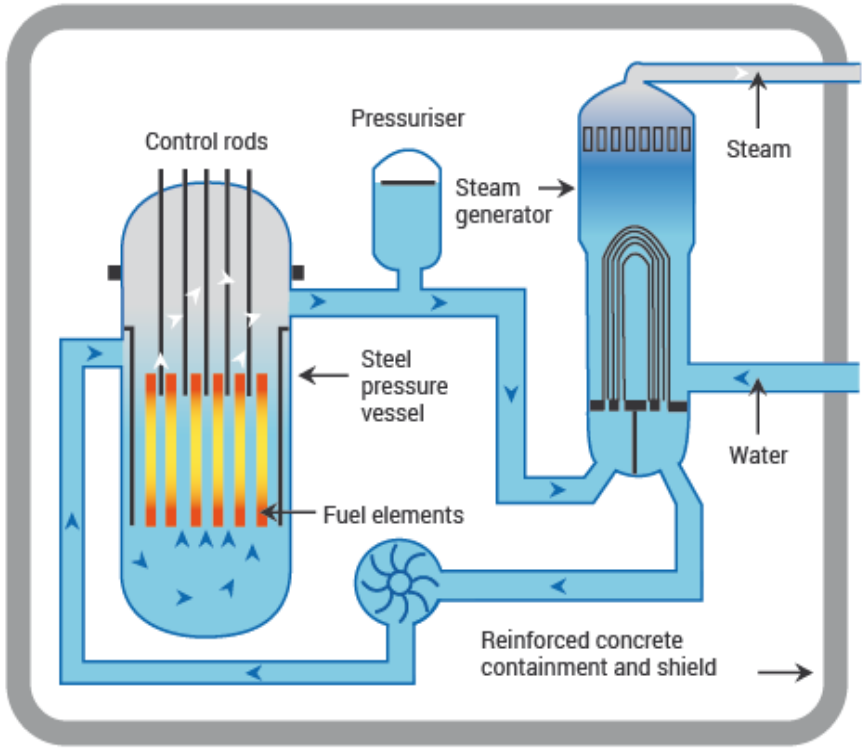


Data is from European Nuclear Society web site, as of 2016 November,

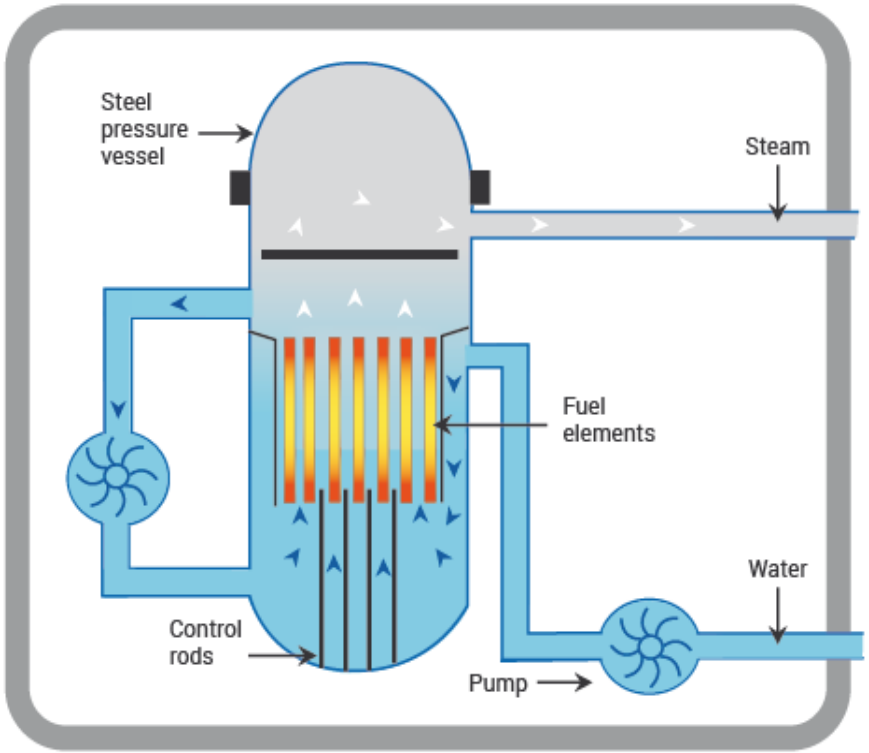
https://www.euronuclear.org/info/encyclopedia/n/npp-reactor-types.htm

Water-Cooled Reactors (1/2)

Pressurised Water-Cooled Reactor (PWR)

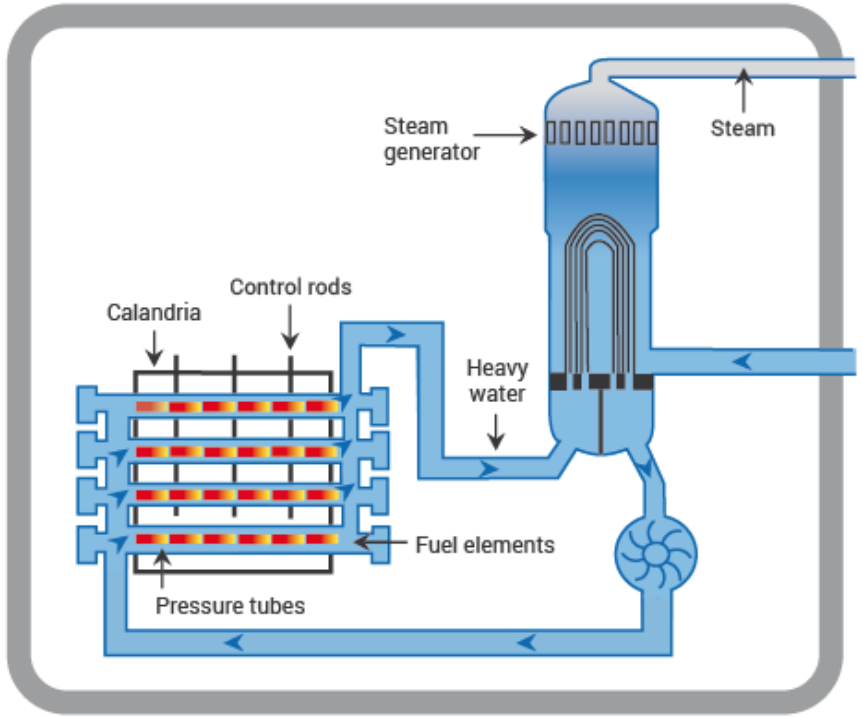


Boiling Water-Cooled Reactor (BWR)



Water-Cooled Reactors (2/2)

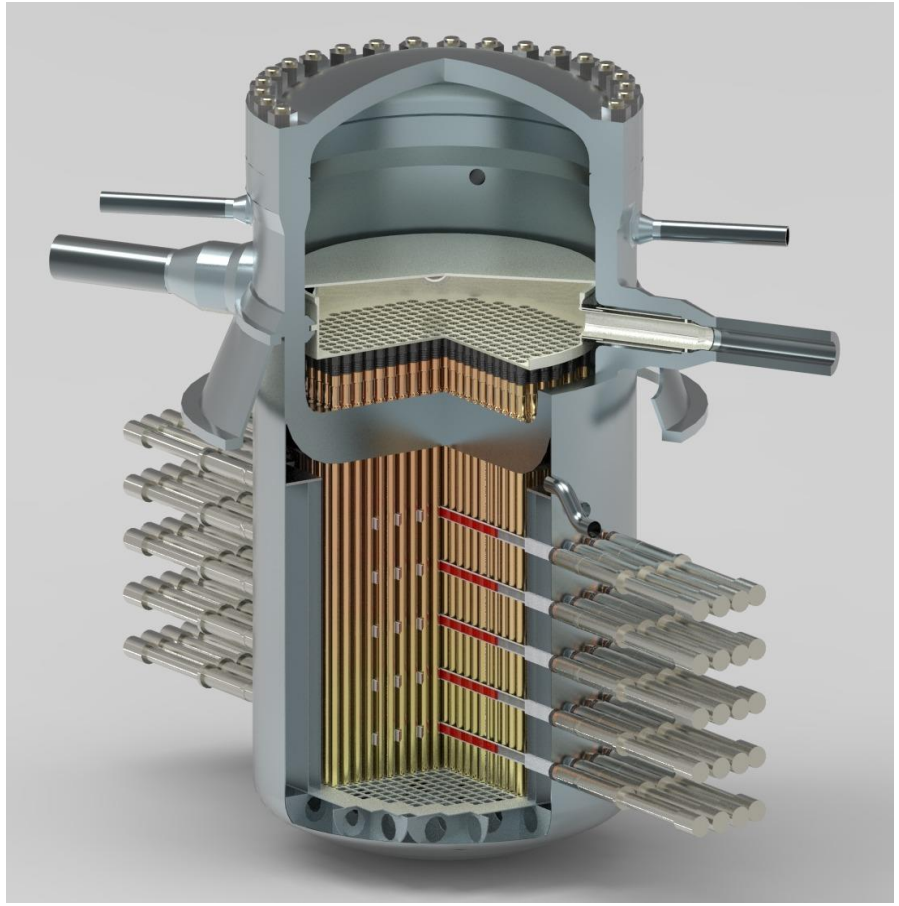
Pressurised Heavy Water-Cooled Reactor (PHWR)



PHWR

- Similar to PWR except:
  - Coolant is heavy water
  - Moderator is heavy water
  - Uses fuel channels instead of a reactor vessel
- Fuel is natural uranium
- Canadian fleet: CANDU reactor

Advanced Reactors (1/3)



The term “Advanced Reactor” is generally used for non-water cooled reactors employing novel technologies. Some examples:

- Sodium-cooled reactor
- Lead-cooled reactor
- Molten-salt reactor
- Very high temperature gas-cooled reactor

Although some of these reactors have been built and operated in the past, they have not been widely deployed and they are making a comeback.

Advanced Reactors (2/3)

Most ARs have inherent safety characteristics and employ passive safety principles resulting in order(s) of magnitude lower probabilities of core melt and large release to environment

Inherent and Passive Safety Features

- Physics of the reactor doesn't allow power excursions (most ARs reduce power if the fuel temperature increase above a certain value – i.e. negative temperature reactivity)
- Reactor Safety Systems automatically activate when needed without active controls to avoid accidents in the event of malfunction.
- Safety systems rely on forces of nature, i.e. gravity, radiation and natural convection, not active components needing external power

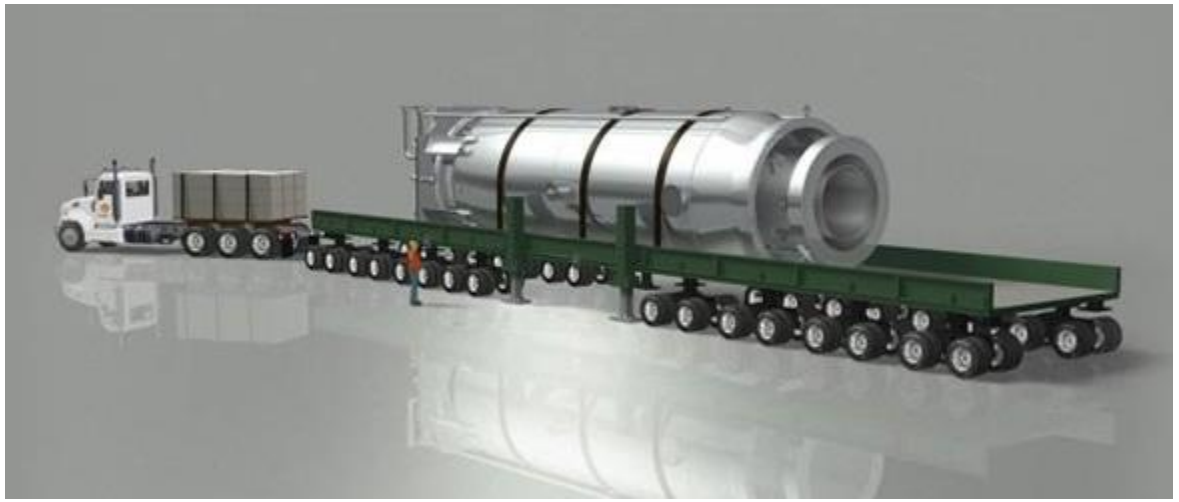
Advanced Reactors (3/3)

Other Distinguishing Features

- High retention of fission products in severe accidents (minimal effect to environment and significantly reduced emergency planning zones)
- Some ARs are Fast Reactors. These reactors burns nuclear fuel more efficiently and decreases waste production.
- Hybrid generation adaptability (e.g. hydrogen production, desalination, etc.) and/or load following

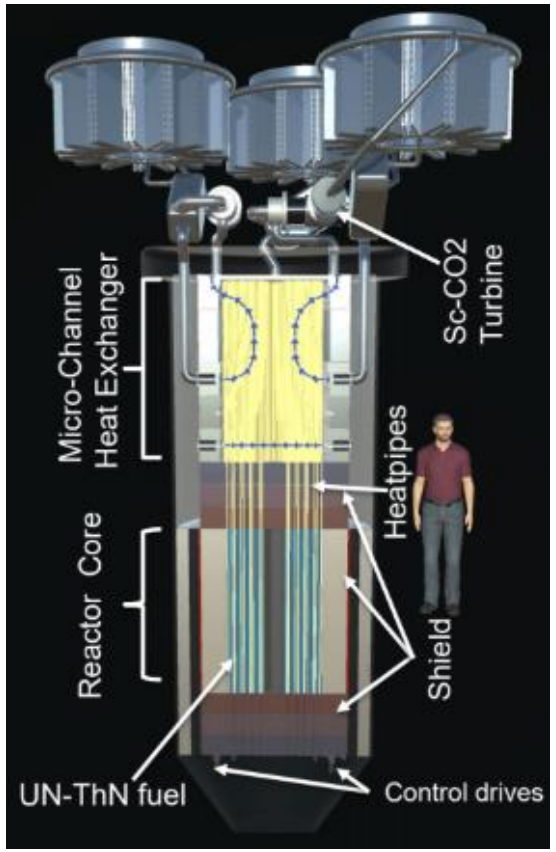
Small Modular Reactors (SMRs)

- Commonly accepted definition of SMR: Power ≤ 300 MWe
- Internationally, there are more than 100 SMR concepts
- Most SMRs employ Advanced Reactor technologies
  - *have inherent and passively safety system features*
- Suitable for edge-of-grid and off-grid applications



- Factory manufactured
- Transportable
- Lower capital risk

Very Small Modular Reactors (or Microreactors)



- Smallest SMRs with power ratings <10 MWe* are called Very Small Modular Reactors (VSMRs) or Microreactors.

  * This is an arbitrary definition based on the power ranges of SMRs proposed for on-grid and off-grid applications.

- Suitable for off-grid locations
- 100% factory built
- Installation in months is possible
- Autonomously operated, remotely monitored

Los Alamos Megapower microreactor concept.
In 2018, NASA built and demonstrated a 1 kWe version of this reactor.

Pan-Canadian SMR Roadmap

(https://smrroadmap.ca/)

Economics of SMRs

Megan Moore, Operations Research Analyst

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

DELIVERING THE
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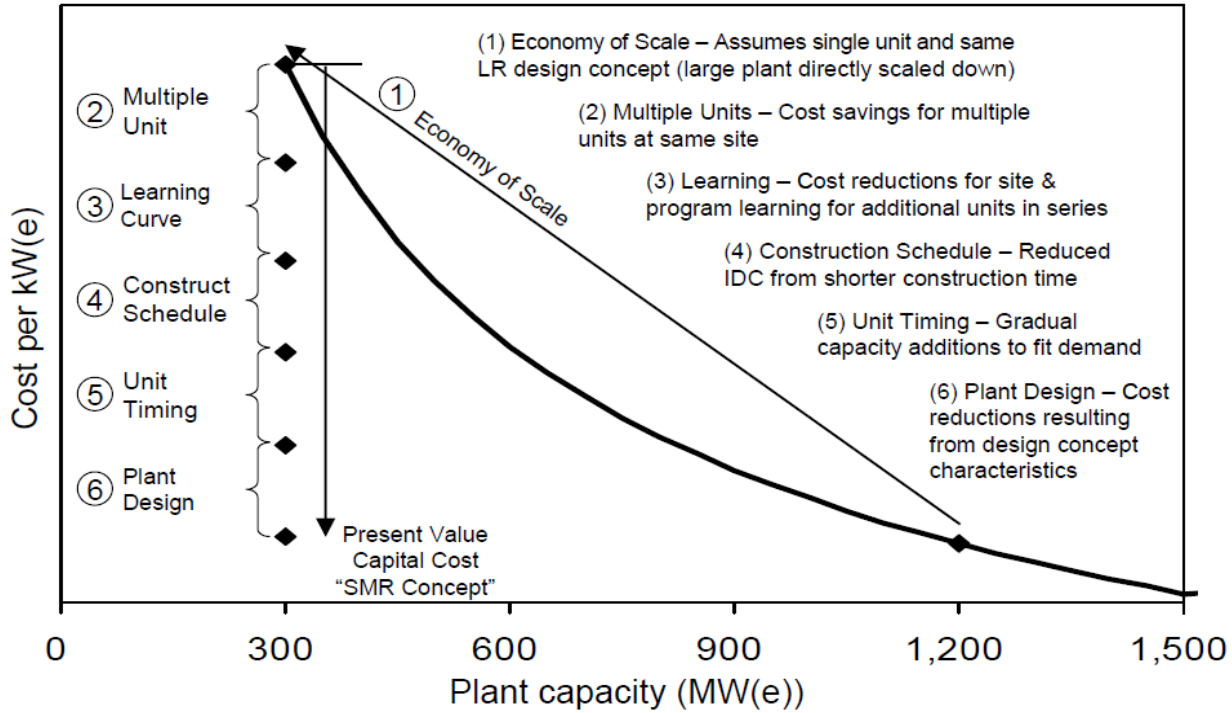
Economics

How are SMRs going to compete?

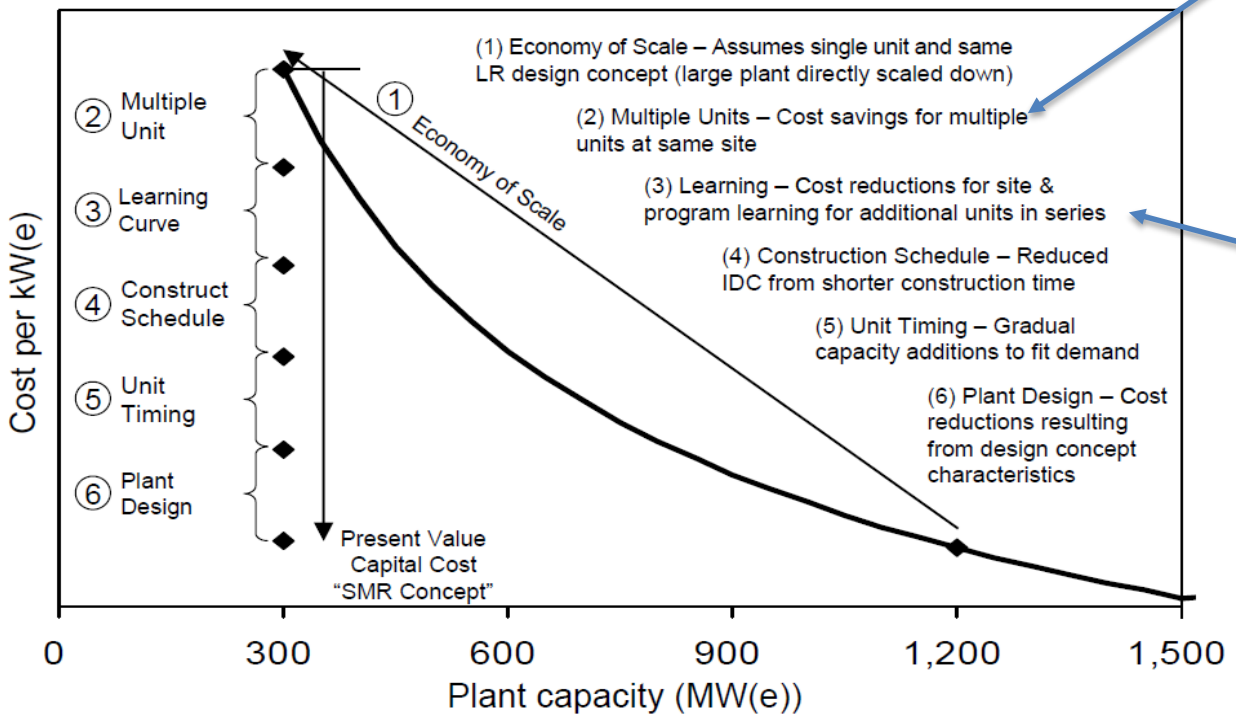


SMRs replace
"Economies of Scale"
with
"Economies of Many"

IAEA, 2013, "Approaches for Assessing the Economic Competitiveness of Small and Medium Sized Reactors", No. NP-T-3.7, Vienna.

Economics

How are SMRs going to compete?



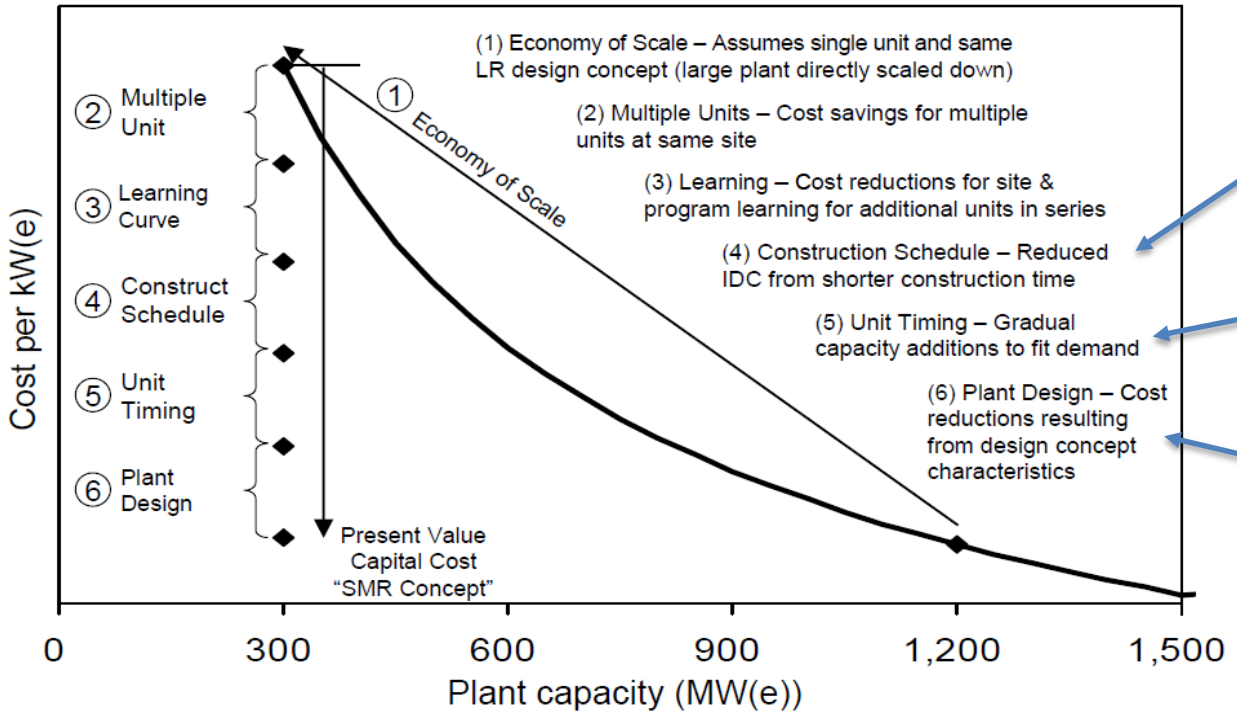
(2) SMRs are often designed to be built in sets. Sometimes with multiple reactors sharing key systems such as the turbine system or control room.

(3) SMRs are also designed for factory fabrication, increasing learnings because the same people repeat the same tasks for many SMRs regardless of deployment locations.

IAEA, 2013, "Approaches for Assessing the Economic Competitiveness of Small and Medium Sized Reactors", No. NP-T-3.7, Vienna.

Economics

How are SMRs going to compete?



(4) Factory fabrication also decreases construction time with decreases interest paid during construction.

(5) Smaller size means you can better match demand and don't end up with excess. If demand grows, the SMR site can grow with it.

(6) New SMR technology and plant design concepts can also be used to reduce costs.

IAEA, 2013, "Approaches for Assessing the Economic Competitiveness of Small and Medium Sized Reactors", No. NP-T-3.7, Vienna.

Economics

Factors that Affect the Cost of an SMR

- SMRs covers a very broad set of reactors and potential applications resulting in different costs.
- Some key factors that affect cost:
  - Maturity of designs
  - Fuel Type
  - Location
  - Number of reactors in the fleet
  - Interest rate & time to construct
  - Staffing regime

Economics

Potential SMR Markets

On-Grid: 150-300 MWe

- Large inter-connected electricity grid.
- Replace fossil fuel plants.
- Increase flexibility of grid.

Industry: 10-80 MWe

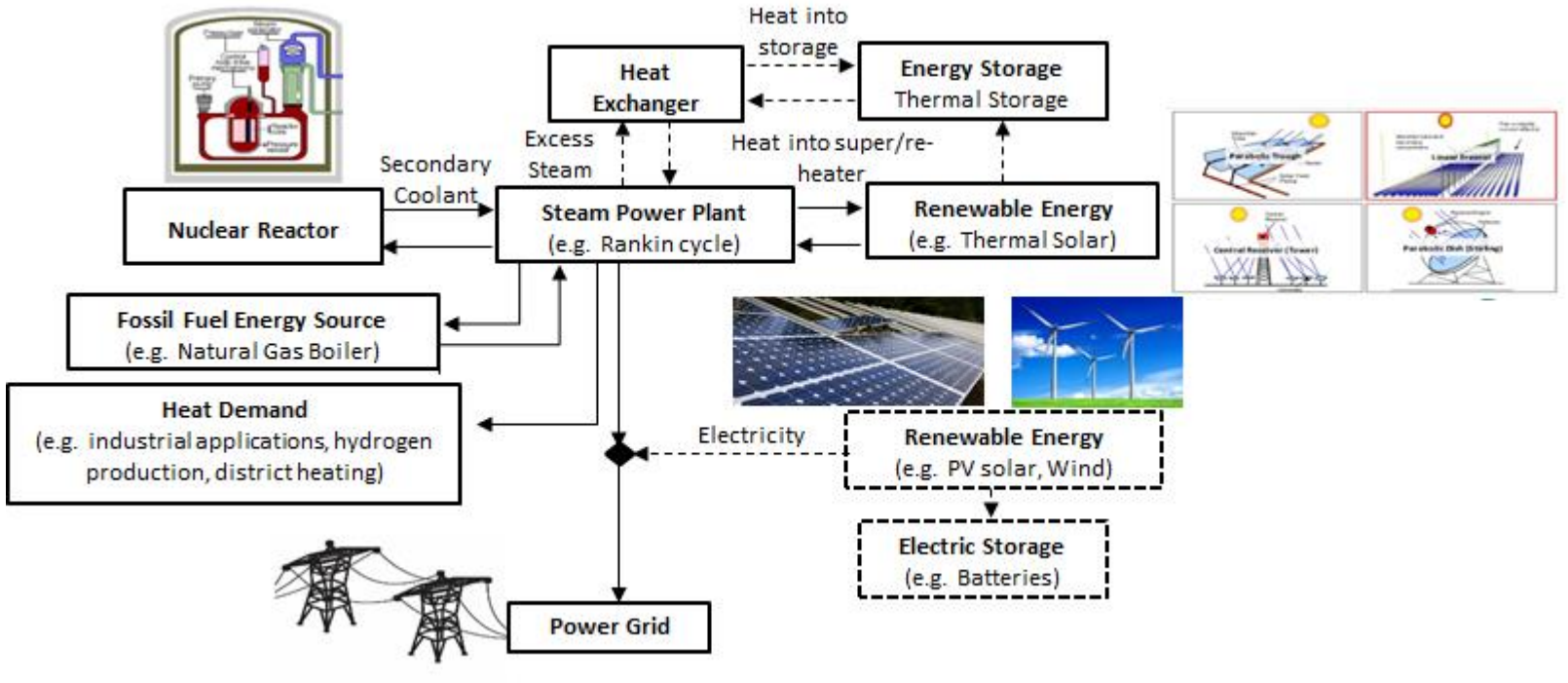
- Provide heat and electricity to industrial processes.
- Reduce emissions, improve reliability.

Off-Grid: 1-10 MWe

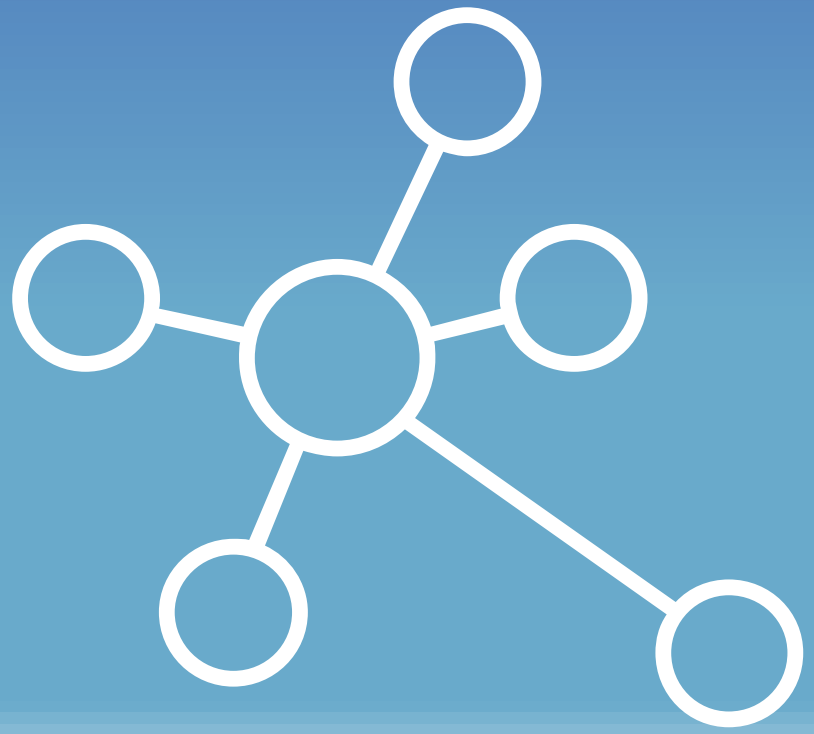
- Alternative to diesel generators to reduce emissions and provide price stability.
- Support district heating and/or desalination.

Economics

Potential Synergies with Other Technologies (Hybrid Energy Systems)



Recent Developments in SMR Space



Vendors Making Deployment Progress

Licensing Submissions

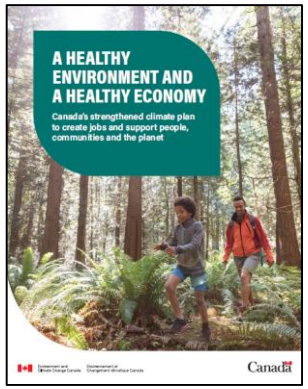
- X-Energy recently made combined phase 1 and 2 CNSC VDR submissions.
- Bringing the total to 10 vendors including:
  - Terrestrial Energy Inc. (Integral Molten Salt)
  - Ultra Safe Nuclear Corporation (High Temperature Gas)
  - LeadCold Nuclear Inc. (Molten Lead)
  - ARC Nuclear Canada Inc. (Liquid Sodium)
  - Moltex Energy (Molten Salt)
  - SMR, LLC (Holtec – Pressurized Light Water)
  - NuScale Power LLC (Integral Pressurized Light Water)
  - U-Battery Canada ltd. (High Temperature Gas)
  - GE-Hitachi Nuclear Energy (Boiling Water Reactor)
- Global First Power is in the licensing process for Chalk River Demonstration.

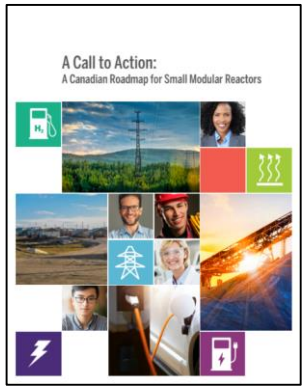
Partnering with Operators

- Several vendors working with existing Canadian operators to help bring reactor to market.
  - Ontario Power Generation now part owners of Global First Power (USNC tech).
  - Moltex Energy and ARC Nuclear working with NB Power and NB government for first reactor siting.
  - Other partnerships in discussion.

Canadian Landscape

A Coordinated National Effort





Federal

- SMR Roadmap (2018)
- SMR Action Plan (2020) [109 participating orgs, 450 actions]
- Climate Change Plan
  Minister calls out Nuclear to achieve 2050 zero emissions
- Nuclear included in Hydrogen Strategy

Provincial

- Provincial MOU: ON, NB, SK, (AB?) Defined Pan Canadian Approach
- Stream 1: On grid replacement 2026+
- Stream 2: On grid AR 2030+
- Stream 3: Off grid Microreactor 2026+

Industrial

- Traditional Nuclear
- Mining
- Oil and gas
- Hydrogen

Questions?

Additional Resources:

- WNN's SMR article at https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx
- Canadian SMR Roadmap https://smrroadmap.ca/
- IAEA SMR website https://www.iaea.org/topics/small-modular-reactors
- "Resources" menu in GAIN website https://gain.inl.gov/SitePages/Home.aspx
- CNSC Licensing Activities https://nuclearsafety.gc.ca/eng/reactors/research-reactors/other-reactor-facilities/small-modular-reactors.cfm
- NWMO waste management https://www.nwmo.ca/